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Unfortunately for the large number of flight enthusiasts, except for some advances made immediately after the World War, there has been no important development in the cheap, light airplane field. One of the main reasons for this may be considered the lack of suitable engines. The object of the present paper is to consider the interaction of engine, propeller, and airplane for this low-power range, the discussion being presented in such a form as to provide the engine builder with a basis in his selection of the type of engine required, a suitable selection being possible only in connection with considerations on the best possible propeller. Guiding rules and instruction in the design of a propeller are found only very rarely in engineering literature. Although the theoretical treatment of this problem is unsuited for the restricted limits of a handbook or a short article, it is nevertheless desirable that at least a discussion be given as to the choice of a propeller on the basis of wind-tunnel measurements together with the characteristics and dimensions of several families of propellers.

For the purpose of a general discussion, the experimental data for a single family of propellers are not sufficient. We shall therefore make use of a series of envelopes whose construction is shown in figure 1. The curves are plotted in the usual coordinates, the power coefficient $K_d = 6.16 \dfrac{N}{\rho\ n_s^3\ D^5}$ (where N is the engine output in horsepower, ρ the air density = 1/8 at sea level, n_s the speed in revolutions per second, and D the diameter in meters) being taken as ordinates against

*"Motorgleiter und Leichtflugzeuge. Betrachtungen über Motoren und Luftschrauben." Flugsport, vol. XXIX, no. 24, November 24, 1937, pp. 663-671.

the ratio $\lambda = 0.318 \frac{v}{n_s D}$ (where v is the air velocity in meters per second) as abscissas. The figure gives the curves of equal efficiency, for η = 80 percent, of six propeller families (reference 1). Below and to the left of these lines the propellers of the system give lower efficiency; above and to the right, higher efficiency. About the corresponding curves of each of the families, an envelope is drawn, and this envelope indicates, with a certain degree of accuracy, the region within which, in the present state of development, an efficiency of at least 80 percent may be attained by the usual methods.

In selecting a propeller it is to be taken from that family of propellers whose characteristic curves coincide with or lie closest to the envelope. As seen from the diagram, the distance between the envelope and propeller characteristics is considerable at some places. The gap would be filled out by a family of propellers whose blade number, blade plan form, and blade width lie between the two families touching the envelope near this gap. The region between the three-blade propeller described in reference 1, and the four-blade propeller with $H_o/D = 1$ thus belongs to a three-blade family whose dimensions and characteristics, however, are unknown.* Figure 1 and the diagrams derived from it are therefore not sufficient for all cases of propeller design. They give only the best attainable values as regards efficiency, diameter, and speed, but provide no information as to the blade number, pitch, plan form, etc. Figure 2 shows these envelopes plotted for the total efficiency range that is met with in practice. The scale is logarithmic for both axes. Since, in the discussion on light airplane engines that follows, the maximum allowable speed of rotation and smallest possible diameter are factors of importance, there are shown on the figure two curves which satisfy these conditions. They represent the connecting curves between the points of contact of the lines of equal efficiency with straight lines of a definite slope, the straight lines being derived as follows.

Substituting in the formula $K_d = 6.16 \frac{N}{\rho \, n_s^3 \, D^5}$ for

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*Further data on metal propellers with two or three blades and on the effect of blade plan form and pitch distribution, will shortly be published in Flugsport.

n_s, the value $0.318 \frac{v}{\lambda D}$ and for D, $0.318 \frac{v}{\lambda n_s}$ and combining the product of v, N, ρ and the numerical coefficients by the single constants c_1 ...., we obtain $K_d = c_3 \frac{\lambda^3}{D^2}$ and $K_d = c_4 \lambda^5 n_s^2$. From these it follows for D = constant, that $K_d = c_5 \lambda^3$, and for n_s = constant, $K_d = c_6 \lambda^5$. Both of these equations are represented in the logarithmic coordinate system by straight lines with the required slopes.

In order to obtain a clear picture of the interaction between the engine, propeller, and airplane, it is necessary to assume certain simplifications. It is first assumed throughout that the air density is the same; namely, that corresponding to sea-level flight. The engine power N, is next brought into relation with the airplane speed v. If we consider the most important flight condition in the case of power gliders and light airplanes - namely, flight with maximum velocity of climb - only slight differences appear with respect to the airplane speed under this condition. To keep the power required low, we must consider our choice of wing loading. Furthermore, since the shape of the polar, and hence the value of the lift coefficient for flight with high climb velocity, can only be slightly affected for a machine with a 20-horsepower engine, for example, the airplane speed for which the highest propeller efficiency is obtained, always remains practically the same. This velocity may be assumed to lie between 65 and 70 kilometers per hour (40 and 45 miles per hour). With increasing engine power the wing loading increases, since the power loading in general decreases, and there is thereby obtained in spite of the higher power requirement - or rather, in spite of the higher sinking velocity - a sufficient climb velocity.

Figure 3 shows the relation between the engine power and the velocity of flight for the most rapid climb. The curve represents the mean values of a very large number of computation results. A further justification for the particular choice of climbing flight as the basis for our consideration is not necessary since all light-airplane pilots are agreed that cruising flight and, in particular, level flight at full throttle, yield in importance when compared with climb after take-off or in difficult country.

The first and most important question in selecting a

propellor is that of the best efficiency that can be attained for the given revolution speed and power (the airplane speed is obtained from fig. 3) and how large will be the propeller diameter. The answer is given by figure 4, which is based on the curve of maximum revolution speeds (fig. 2). It is generally known that the efficiency of a low-speed propeller is better than that of a high-speed propeller. Since, on the other hand, light airplane engines generally operate at high speeds, that point of the propeller characteristic must be taken which corresponds to the maximum revolution speed. Again, in the case of geared engines with high reduction ratios, the propeller diameter becomes inconveniently large. In this case the point of the characteristic is to be chosen at which the diameter is the minimum.

As shown by the curves for n_{max} and D_{min} in figure 2, the propeller with highest speed, for a given efficiency, is not simultaneously the one with the smallest diameter. Within the range that occurs in practice, however, the differences are so slight that a separate consideration of these two cases is hardly worth-while. The case of maximum revolution speed is the only one therefore that has been used as a basis for the following computations and curves. It may be seen from figure 2 that the distance between the two curves decreases with increasing efficiency. At the maximum value of the latter the two curves coincide.

Figure 4 shows curves of equal efficiency and equal diameter as functions of engine power (airplane speed) and engine speed. The curves were computed with the aid of the known K_d and λ formulas in which, for a definite efficiency, the values of the propeller characteristics obtained from the n_{max} curve were substituted. Points are also indicated on the figure which correspond to the light-airplane-engine designs of the last ten to fifteen years. The curves show that for an engine, for example, of 20 horsepower and 3,000 revolutions per minute at a forward speed of about 66 kilometers per hour (40 miles per hour), only 60 percent may, in the most favorable case, be utilized. The corresponding propeller diameter will be less than 1.2 meters (3.94 feet). It is to be noted particularly that the choice of a larger diameter would show no advantages. The efficiency will be reduced as long as the revolution speed is not lowered. Only for the thrust at standstill would a slight advantage result

since the disk loading will be lower, whereas the efficiency ξ, namely, the ratio of the actual to the theoretically attainable thrust, will be practically unchanged. Since, however, the velocity in take-off comes sufficiently close to the velocity for maximum climb, for which the efficiency will again become lower than that for the smaller diameter propeller, there is hardly any advantage gained in increasing the propeller diameter above that based on the best value for the climb condition, even for the take-off.

It follows from figure 4 that the attainment of the absolute maximum efficiency of 88-89 percent - only the free jet efficiencies are here considered; losses through mounting the propeller are still to be taken into account - requires very low speeds and inconveniently large diameters. An efficiency of 80 percent will, in the case of a 20-horsepower engine, be attained only at a speed of about 750 revolutions per minute, and at a diameter of more than 2.5 meters.

With increasing power the efficiency relations become more favorable - a consequence of the relation between engine power and airplane speed. With engines of higher power therefore somewhat higher rotational speeds may be used. An improvement is also attainable in the lower range for powers less than 20 horsepower. In this case the improvement results from the rapidly decreasing disk loading due to the lowered engine power, while the forward velocity only slightly decreases since a wing loading of less than 20 kilograms per square meter is hardly ever used, even in the case of airplanes with very low engine power. Engines of about 20 horsepower are therefore the most exacting as regards speed reduction. The propeller diameter, however, increases with the power - the rise up to 20 horsepower being somewhat steeper. It is clearly evident from figure 4 that the majority of existing engines do not admit more than a 65-percent propeller efficiency in climbing flight. Only a few types attain more than 75 percent. In the lower power range, it is the old Mercedes with its reduction ratio of 1:3, and several older 50-horsepower low-speed 3-cylinder engines.

In order to be able to draw further conclusions, we must now consider the engines more in detail. In figure 5, the weights per unit cylinder displacement in kilograms per liter of the engines of figure 4, are plotted against the total displacement. Within the range limited by the

two thin curves, the dot-dash curve should represent the practical or safely attainable lower limit for engines not gear-driven. The corresponding total weight is given by the dashed straight line. For the mean power range, we may write $G_{kg} = 20 + 10\ V$ where V denotes the total cylinder displacement in liters.

Figure 6 shows the mean effective pressures of 4- and 2-stroke-cycle engines plotted against the cylinder volume. In spite of the considerable scattering of the points, no important effect of the cylinder displacement can be established for the 4-stroke-cycle engine. It is known that the more powerful airplane engines of 2-3 liter displacement, attain the same pressures. In the case of the 2-stroke-cycle engines, the topmost point corresponds to an engine with a supercharger. On account of the restricted possibilities of supercharging so small an engine and still keeping the structure within reasonable limits, this point will not be taken into consideration. Since the mean effective pressure shows no tendency to drop off as the cylinder dimensions are increased, it is to be concluded that several of the engines, including some that have for some time been built outside Germany with definitely large cylinders, were designed somewhat "optimistically." On account of this uncertainty, we shall not consider the 2-stroke-cycle engine, in spite of its higher power per unit volume, and hence also, per unit weight within a definite range.

For the 4-stroke-cycle engine, we set the mean effective pressure as equal to 8.5 atmospheres. We thus obtain $V = 106\ \frac{N}{n}$ and $G = 20 + 1{,}060\ \frac{N}{n}$ (V = total displacement in liters, N = horsepower, n = engine speed in revolutions per minute, G = engine weight).

Let us now consider the following problem for a single- and two-seater: A useful output, i.e., engine output times propeller efficiency, of 15 and 30 horsepower for a single- and two-seater, respectively, is required. What should be the speed of the engine in order that its weight should be a minimum, and how do weight, displacement volume, and power supplied to propeller shaft vary with the design speed? The velocity in climb according to figure 3, is assumed as 66 and 82 kilometers per hour for single- and two-seater, respectively, corresponding to a power supplied of 20 and 40 horsepower for a single- and two-seater, respectively.

We start with the efficiency η. Determine the required power supplied to the propeller shaft, and from this the diameter (only as an intermediate value) and the rotational speed; furthermore, the cylinder displacement and the weight. The results are shown in figure 7. The volume decreases with increasing engine speed somewhat hyperbolically; the weight decreases rapidly at first, then from 3,000 to 4,000 revolutions per minute, more slowly. The power supplied to the propeller shaft increases correspondingly to the decreasing efficiency. In order to obtain as light engines as possible, high engine speeds must be used in spite of the associated lower propeller efficiencies. This method is not, to be sure, economical, since the fuel consumption, as a result of the higher power supplied to the propeller, is considerably higher than is the case for low-speed engines. In increasing the speed from 2,000 to 4,000 revolutions per minute, the fuel consumption increases by 20 percent. The curves of figure 7 apply only for direct propeller drive.

In order to bring out the effect of the rotational speed at constant engine power and the advantages of a reduction gear, the climb outputs of a powered glider with various engines of equal power will be computed. We assume a flying weight of 275 kilograms with an engine of 20 horsepower at 2,700 revolutions per minute and 28.5-kilogram weight (according to fig. 5) and a wing loading of 20 kilograms per square meter - that is, a wing area of 13.75 square meters; lowest sinking velocity, 1.4 meters per second at 68 kilometers per hour flight velocity. These figures correspond approximately to what is meant by a "powered glider" as specified in the requirements for competitive flying.

Strictly speaking, it must be determined in each case at what velocity the best climb output is attained. Since the propeller efficiency steadily increases with velocity, whereas the sinking velocity only slowly increases, the greatest climb velocity will be attained not at the velocity of least power required, but somewhat above it. The difference, however, is so slight that it can be neglected when compared to the simplification attained by the association of a definite velocity with each engine power.

Figure 8 shows how the displacement and weight of a direct-drive engine - always assuming the power supplied to the propeller to be 20 horsepower - vary with the rotational speed. For a gear-driven engine the crank speed

has been arbitrarily fixed at 3,300 revolutions per minute. As may be seen from the flatness of the curves of figure 7, the results are only slightly affected by the change in speed. The displacement becomes 0.64 liter. The increase in weight resulting from the use of the gears, is assumed to be from 8 to 12.5 kilograms, depending on the reduction ratio - this weight including additional masses for balancing the crankshaft so as to secure smooth operation and increased weight of the propeller on account of its larger diameter. Figure 8 shows that for propeller speeds below 1,350 revolutions per minute, a gear-driven engine gives a lighter construction than an engine directly driven, for which the loss in output due to lowered engine speed is made up by increasing the cylinder displacement. Another curve on figure 8 shows, for this particular case, the dependence of the propeller efficiency on the rotational speed.

From the values for engine weight and efficiency the maximum climb velocity was computed and the results plotted on figure 9. At 1,350 revolutions per minute, the two types of drive are again equivalent. The scale on the right side gives the percent change in the climb velocity. At 1,000 revolutions per minute, there is a gain in climb velocity of 30 percent for the direct-drive engine, and 33 percent for the gear-driven engine above that at 2,700 revolutions per minute. This difference, for equal engine output, is so great that it seems proper to utilize this advantage even if several difficulties are involved that must be overcome.

Figure 9 shows two other curves that give the increase in propeller diameter with decreasing speed. Since in most of the cases a 2-meter propeller can still be used, no insuperable obstacles are to be met with from this source.

On closer examination of figures 7, 8, and 9, the engine designer is confronted with two tendencies which at first sight appear to contradict each other. If the least possible weight is required of an engine with a definite useful output - engine output times propeller efficiency - then a distinctly high-speed engine is the suitable one to use, the speed not being limited above by the propeller since the efficiency decreases only very gradually in the range above 4,000 revolution per minute. The actual power supplied to the propeller is not to be taken as a measure of the output, but that output is to be considered which is converted into thrust. Such an engine will be uneconom-

ical, however, since it will have a very large fuel consumption based on the useful power. On the other hand, it has the advantage of smaller dimensions which, in connection with the small propeller diameter, results in a power unit that provides the fewest difficulties as regards mounting.

If, on the other hand, the economy - i.e., the best possible utilization of the fuel - is the factor that is given chief importance, then the engine must run at low speed or be provided with a reduction gear. It is here always assumed that the specific fuel consumption is equally high for all engines. It is worth noting that for a 4-stroke-cycle engine which satisfies the formulas developed above, a gear first becomes necessary at propeller speeds of less than about 1,350 revolutions per minute. Above this speed, a slow engine of large displacement has the advantage. These relations hold strictly only for an engine of 20 developed horsepower, but may qualitatively be applied for other power ranges of the light-airplane engine.

Two-stroke-cycle engines do not adapt themselves to this general method of computation. In the first place the useful pressure decreases with increasing cylinder size. Secondly, cylinders of more than about 350 - at most 500 - cubic centimeters, cannot be used at present since at somewhat high mean effective pressures, the heat conduction cannot be controlled. Thirdly, on account of the separate charging pump required for the 2-stroke-cycle engine, only a small number of cylinder arrangements is possible. For these small engines a useful, reliable compressor would be of great value. In spite of all efforts, however, no definite success has been attained in this field.

From the point of view of the engine builder, there is a tendency away from too low speeds, such as would be required according to figure 9. The engine becomes large and therefore also heavy although, and this again is particularly stressed, the higher weight has already been taken into account in the comparison computation. Mass balance may be partly achieved through the use of large counterweights, while even running for a not particularly heavy propeller still remains unsatisfactory. These disadvantages disappear when a gear is used. The engine then again becomes smaller and the weight of the gear is not excessive when the speed is not reduced below the limiting speed of 1,350 revolutions per minute.

A disadvantage of a propeller with high-gear reduction is the difficulty in starting the propeller. This difficulty can be removed, however, by the use of a starting lever that acts on the crankshaft.

Summarizing, the following concluding statements may be made. Light-airplane engines are conveniently designed as high-speed engines (the term "high-speed" being understood to mean speeds of 3,000 to 4,000 revolutions per minute). In those cases where a definite useful power, to be expressed conventionally by the maximum-climb velocity of the airplane, is to be attained with the smallest engine weight, the propeller should be the direct-drive type. If economical operation - that is, the best possible flight performance for a given power developed by the engine, or for a given fuel consumption is the factor of importance - then a gear-driven propeller is recommended, the reduction ratio of which is determined by the maximum allowable propeller diameter. The propeller speed will then be about 600 to 1,000 revolutions per minute.

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

REFERENCE

1. Windler, Ray: Tests of a Wing-Nacelle-Propeller Combination at Several Pitch Settings Up to 42°. T.R. No. 564, N.A.C.A., 1936.

Weinig: Luftfahrtforschung, Bd. 14, Lfg. 4/5.

Watts: Jour. R.A.S., July 1936.

Flugsport, 1935, p. 571 ff.

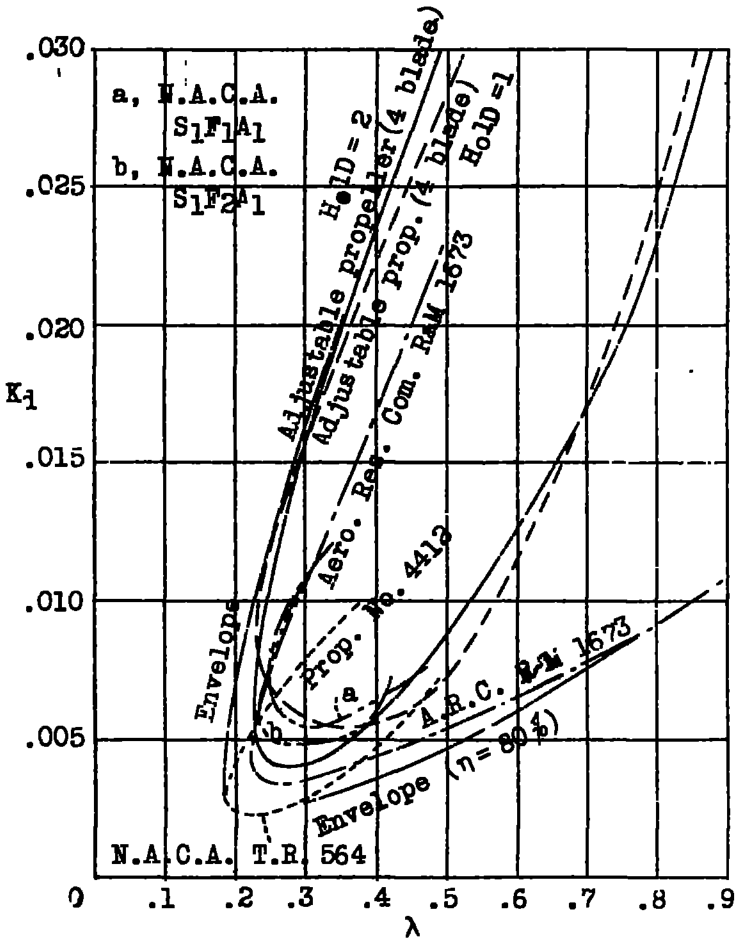


Figure 1.- Curves of equal efficiency for six sets of propellers and envelope.

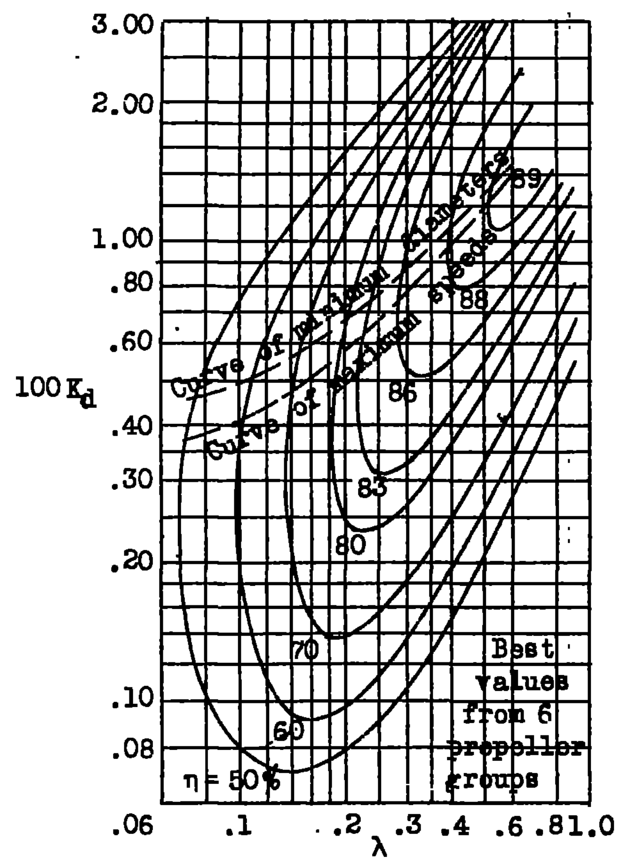


Figure 2.- Efficiency curves for propellers which in the present stage of development represent approximately the upper attainable limit. Operating conditions of propellers of minimum iiameter and maximum speed.

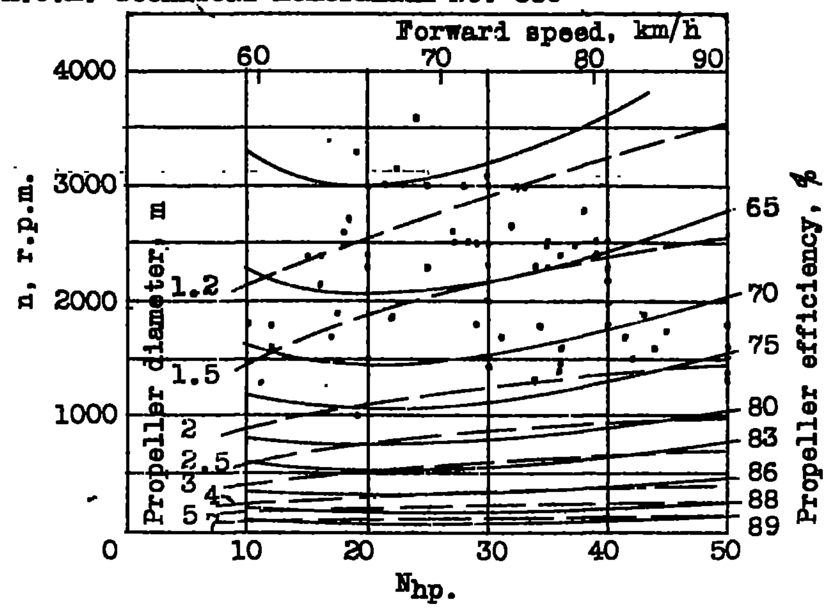
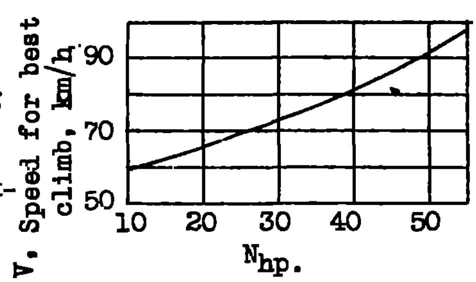


Figure 4.- Diameter and best efficiency of propellers as a function of engine power and speed for the climb condition.

Figure 3.- Average curve showing the relation between the engine output and forward velocity at the condition of maximum rate of climb of powered gliders and light airplanes.



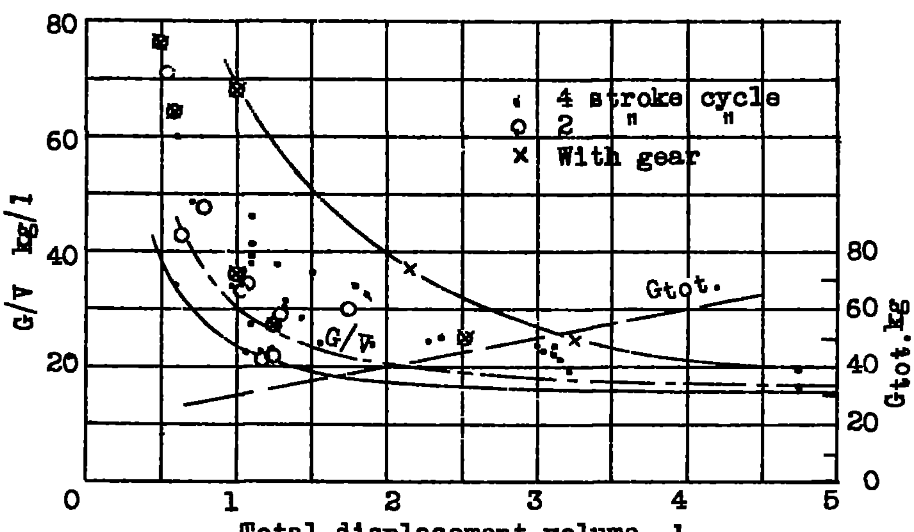


Figure 5.- Weight per liter of light airplane engines as a function of the total displaced volume and the absolute weight for good engines The curve marked G_{wt} corresponds to the dot-dash curve G/V.

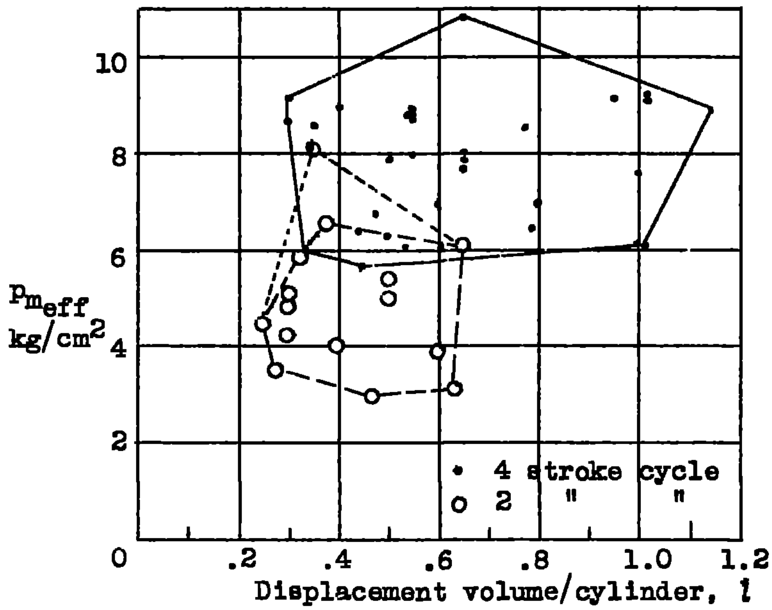


Figure 6.- Mean effective pressure at maximum output as a function of cylinder displacement.

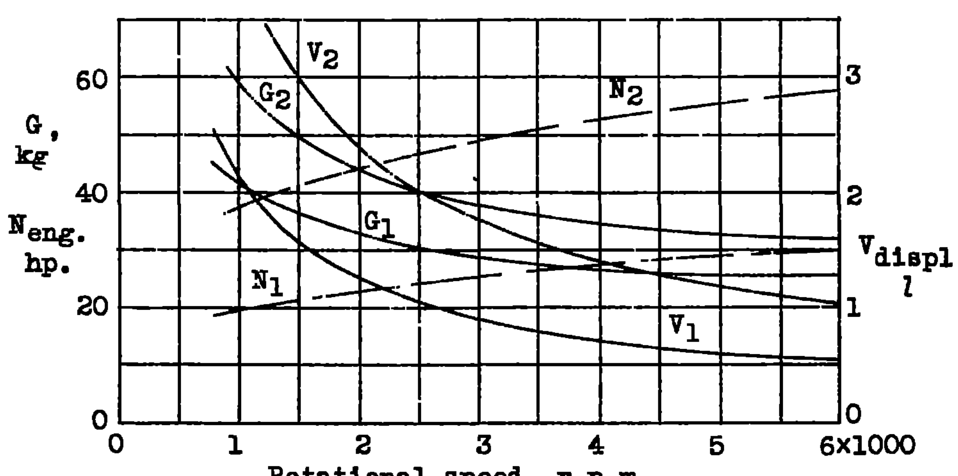


Figure 7.- Cylinder displacement, weight, and power supplied to propeller shaft for engines with a useful propeller output of 20 hp. as a function of the rotational speed.

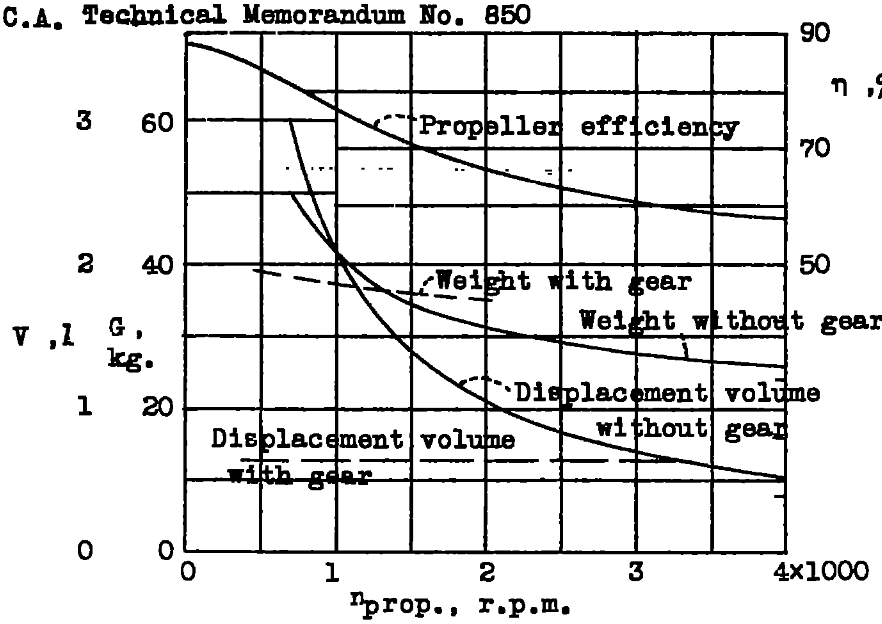


Figure 8.- Cylinder displacement and weight of engines of 20 developed horsepower with and without gear as a function of the propeller revolution speed. Propeller efficiency as a function of the speed.

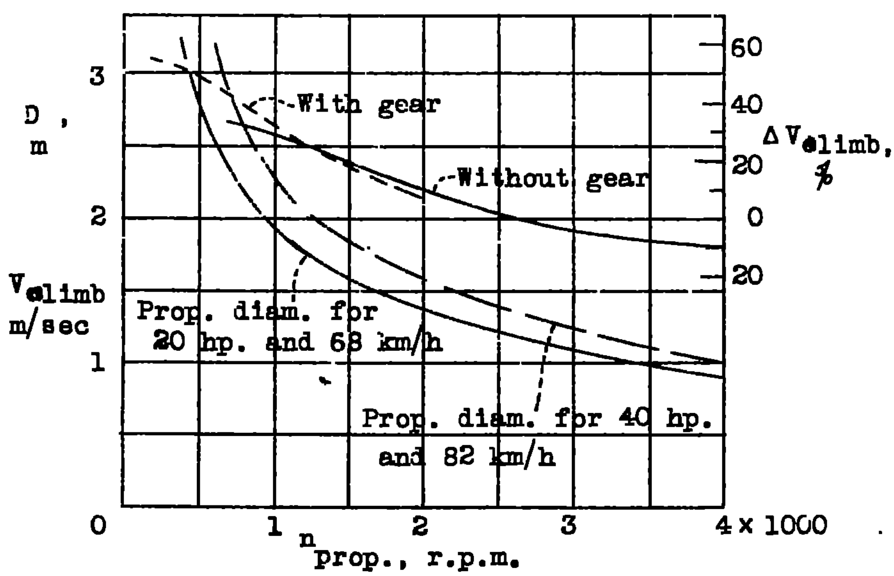


Figure 9.- Maximum climb velocity of a powered glider with 20 hp. engine as a function of the propeller revolution speed. Effect of using a gear, and propeller diameters for 20 and 40 hp.